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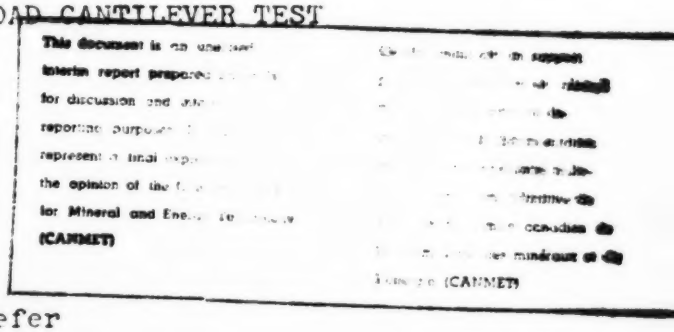
ENVIRONMENTAL CRACKING OF LINE-PIPE AND OTHER STEELS AS SHOWN BY THE RISING-LOAD CANTILEVER TEST



by

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Corrosion Section

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ENVIRONMENTAL CRACKING OF LINE-PIPE AND OTHER STEELS AS SHOWN BY THE RISING-LOAD CANTILEVER TEST

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G. J. Biefer*

ABSTRACT

Eight steels, with yield strengths ranging from 65 to 250 ksi (448 to 1724 MN/m^2), have been evaluated for resistance to environmental cracking (EC) using a rising-load test in which the specimens are loaded as cantilevers. The test medium has been 3.5% NaCl at room temperature, and both free-corrosion and cathodic protection at the potential given by zinc have been investigated.

For service conditions in which a sharp notch or crack might pre-exist or develop, the results indicate that EC might limit the usefulness of the steels with yield strengths greater than 140 ksi (965 MN/m^2). If cathodic protection is used, there is a significant loss of properties even at a yield strength of 100 ksi (690 MN/m^2) and a pronounced reduction in properties above 140 ksi (965 MN/m^2).

A line-pipe steel with a yield strength of 65 ksi (448 MN/m^2) did not show significant environmental cracking when coupled to zinc. This is in agreement with service experience in "sweet" oil and gas transmission pipes that cathodic protection does not by itself cause cracking failures in such grades.

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INTRODUCTION

B.F. Brown developed a test for assessing susceptibility to environmental cracking (EC)* in which notched specimens, precracked in the notch by fatiguing, were loaded as cantilevers[1]. The equations reproduced in Figure 1 were used in calculating the stress intensities K_I at the precrack and specimens were fractured by a step-wise increase ir the applied load. It was found possible to characterize the EC susceptibility of alloys in terms of a critical stress intensity K_{ISCC}, beneath which cracking did not occur within the maximum duration of tests. It was realized that the use of specimens under constant-load conditions might yield more definitive results, but this was ruled out in Brown's early work because of the much higher demand for specimens and testing racks that would have resulted.

In the initial cantilever tests conducted at the Physical Metallurgy Division (PMD), step-loading was used[2], but some disadvantages of the technique became apparent. Unless considerable care was taken, shock-loading of the specimen could occur, and the requirement that the load be increased at regular intervals during the day interfered unduly with other work. Furthermore, unless the specimen broke rather rapidly, the end of the working day or, even more, the weekend, caused an interuption in the loading program. Practically speaking, it was impossible to treat all specimens in the same way.

*Environmental cracking is used here as a general term including both hydrogen-embrittlement cracking and active path cracking.

It was decided to avoid these difficulties by increasing the cantilever load continuously until specimen fracture occurred. The apparatus which was developed has been described in detail[3] and involves dripping water at a constant rate into a container suspended from the end of the cantilever beam. At fracture, the water is shut off and the elapsed time recorded automatically. The nominal stress intensity at fracture is calculated using the equations shown in Figure 1 and is termed K^* to distinguish it from results obtained using other loading methods. As will be seen below, subscripts can be used to indicate the test environment.

The rising-load test is considered to be a general screening test for resistance to EC in that K^* values reflect both K_{ISCC} and the length of the incubation period. Hypothetical examples are shown in Figure 2 which make it clear that K^* will be very nearly equal to K_{ISCC} only when incubation periods are short and crack propagation rates are extremely rapid above K_{ISCC}. If incubation periods are long and/or propagation rates above K_{ISCC} are slow, K^* values can be much higher than K_{ISCC}.

In the rising-load tests at PMD, the initial load is adjusted to give a nominal stress intensity well below the threshold for stress-corrosion cracking K_{ISCC}. For specimens broken under dry conditions, exploratory measurements showed no effect of loading rate on K^* at fracture and it has been found convenient to use rapid rates of 200 ksi $\sqrt{in.}$ per hr (220 MN $m^{-3/2}$ per hr) or more. Each test is therefore completed within 1 hr. For specimens of 18% Ni(250) maraging steel in contact with the standard corrodent of 3 1/2% NaCl, K^* at fracture was found to be strongly dependent on loading rate, particularly at intermediate loading rates[3,4]. To minimize this dependency and also to allow time for the environmental cracks to propagate, rather slow rates of 0.6 ksi $\sqrt{in.}$ per hr (0.66 MN $m^{-3/2}$ per hr) or less were adopted as standard. Tests were usually completed within 200 hr.

Results obtained for a number of different high-strength alloys, including steels in the yield strength range 140 to 250 ksi (965 to 1724 MN/n^2), have been published[4,5]. More recently, the rising-load cantilever test has been extended to lower strength materials including three structural steels with yield strengths of about 100 ksi (690 MN/m^2)[6] and a line-pipe steel with a yield strength of 65 ksi (448 MN/m^2)[7]. The effect of yield strength shown by the above steels is considered of sufficient interest to group the results in the present report.

EXPERIMENTAL

The specimens were of the type shown in Mines Branch Shop Drawing No. 119 (Figure 3). For all the steels but one, which will be specified below, the specimen length lay in the rolling direction such that propagation of the fatigue precrack would constitute L-S cracking[8].

Detailed information has been supplied previously[4,5] on the steels with yield strengths in the range 140 to 250 ksi (965 to 1724 MN/m^2). Some information on lower-strength steels which were tested more recently appears below:

65 ksi (448 MN/m^2) yield strength

Specimens were cut circumferentially from a Stelco X-65 line pipe having a 36-in. diameter and 0.518-in. wall thickness. In work at PMD, this has been designated pipe F. Because rolling direction of the steel is along the pipe axis, the cracks produced in specimens would be equivalent to T-S though they might more properly be termed C-R[8].

100 ksi (690 MN/m^2) yield strength

Specimens were prepared from T-1 steel (United States Steel Co.), CHT-100 steel, (Canadian Heat Treaters, Limited) and from a 1% Cu-3 3/4% Ni alloy developed at PMD[9].

RESULTS

K^* values for eight different steels, fractured in three different environments, are plotted in Figure 4. The environments, and their designations, are

K^*_{dry} : the laboratory atmosphere

K^*_{fc} : free corrosion in 3.5% NaCl

K^*_{Zn} : coupled to zinc in 3.5% NaCl

Coupling to zinc gives a potential of about -1.05 volts SCE. The 18% Ni (250) maraging steel, with a yield strength of 250 ksi (1724 MN/m^2), differs from the rest in that it was held at -1.1 volts by means of a potentiostat.

Because plane-strain conditions are in most cases not obtained, the K^* values of Figure 4 are nominal only. However, the stress intensity equation is of the form

$$K_I = kw$$

where k is a constant indicative of the specimen and precrack size and the length of the cantilever arm and w is the load causing fracture. The k value was more or less constant for the different steels and K^* can thus be considered indicative of the load (in lb or kg) causing the notched specimen to break. This is obviously of direct practical significance.

Free Corrosion Conditions

For the steels with a yield strength of 100 ksi (690 MN/m^2), K^*_{fc} values were only slightly lower than K^*_{dry}, the ratios K^*_{fc}/K^*_{dry} being in the range 0.92 to 0.97. At the 140 ksi (965 MN/m^2) level, the tendency for propagation of an EC crack was somewhat more apparent, with K^*_{fc}/K^*_{dry} being about 0.87. However, the K^*_{fc} values were sufficiently high to suggest reasonably good resistance to EC.

For the steels with yield strengths above 140 ksi (965 MN/m^2), it was not possible to draw a curve over the entire yield strength range, chiefly because the 18% Ni (200) maraging steel (200 ksi, 1379 MN/m^2) was so much more resistant than HP-9-4-25 (190 ksi, 1310 MN/m^2).

Cathodically Protected Conditions

The zinc potential of about -1.05 volts provides cathodic protection to steels. However, hydrogen is generated on the steel surfaces to a sufficient extent to cause EC propagation by a hydrogen-embrittlement cracking (HEC) mechanism for susceptible alloys.

At the 65 ksi (448 MN/m^2) yield strength level, there was little or no susceptibility to HEC, K^*_{Zn}/K^*_{dry} ratios being about 0.97.

At the 100 ksi (690 MN/m^2) yield strength level, maximum K^*_{Zn} values were obtained, but some tendency to HEC was shown, the ratios K^*_{Zn}/K^*_{dry} being in the vicinity of 0.80. At the 140 ksi (695 MN/m^2) level, K^*_{Zn} values had become lower as had the K^*_{Zn}/K^*_{dry} ratios, which were only about 0.55. However, the K^*_{Zn} values seemed high enough to indicate some degree of resistance to EC.

At the 190 to 250 ksi (1310 to 1724 MN/m^2) yield strength level, the steels were extremely susceptible to EC, the K* values actually being lower than those shown at the 65 ksi (448 MN/m^2) yield strength level.

DISCUSSION

The following discussion is based on the trends shown by the eight steels tested. It is appreciated that other steels, untested as yet, could show behaviour differing from that observed up to now.

Dry Conditions

The maximum K^*_{dry} values were shown by the steel with a yield strength of 140 ksi (965 MN/m^2). The steels with higher yield strengths showed decreases in K^*_{dry} with increasing yield strength. While this trend is valid for the experimental conditions used, it should be appreciated that the results cannot be taken as an indication of dry fracture behaviour in a complex structure, in which other factors such as ductility play an important role. Consideration of this topic is beyond the scope of the present report.

Free Corrosion

For the steels investigated, none of which are stainless, free corrosion is not a normal service environment. Over a period of time, free corrosion would cause a general wastage and/or deep penetration due to pitting which might lead to failure, even without EC. The results reported, therefore, are indicative of EC susceptibility in short-term (usually inadvertent) exposures to a corrodent.

The results indicated only a slight degradation of properties at the 100 ksi (690 MN/m^2) yield strength level and a more definite (but perhaps still tolerable) decrease of the ratio K^*_{fc}/K^*_{dry} at the 140 ksi (965 MN/m^2) level. At yield strengths above this, behaviour is difficult to predict but EC susceptibility could be pronounced. In any service application in which sharp notches or cracks are present or may develop, and where exposure to a corrodent seems probable, the use of steels with yield strengths greater than about 140 ksi (965 MN/m^2) may be hazardous.

Cathodically Protected Conditions

Steels in marine and underground service are usually coated and cathodically protected. Providing that cathodic overprotection is avoided, the coating kept intact and fully bonded, and no sharp notches are present or allowed to develop, performance should approach that indicated by the mechanical properties

obtained on smooth specimens in the laboratory. However, maintenance of such ideal conditions cannct be assumed and there is a probability that surface damage of some kind will cause reversion to the lower line of Figure 4. Though it is not always possible to relate laboratory data to service performance, the pronounced drop-off in K^*_{Zn} values above a yield strength of 140 ksi (965 MN/m^2) suggests that the use of steels with yield strengths much above this level would be hazardous.

The X-65 line-pipe steel (steel F), with a yield strength of 65 ksi (448 MN/m^2), showed little or no susceptibility to EC when cathodically protected by zinc. This is in agreement with service experience in "sweet" transmission pipelines[10], in which hydrogen-embrittlement cracking failures have not been observed for line pipe with a yield strength below 90 ksi (621 MN/m^2)[11] except at localized hard spots where the actual yield strength was far greater than the nominal value.

In other work at PMD on specimens cut from commercial line pipe[7], circumferentially cut specimens with the longitudinal weld at their centres were tested as U-bends. Steel F and two other steels with similar yield strengths did not show EC even after a 4-week immersion in 3.5% NaCl solution, coupled to zinc. The same steels were tested in the same configuration in 3.5% acetic acid saturated with H_2S, and showed through-specimen cracking after 1 week. It appears, therefore, that the use of a more strongly hydrogen-embrittling solution such as the above might have produced measureable EC in the rising-load cantilever test, and permitted a quantitative assessment of different line-pipe steels. Such testing has been postponed because of difficulties in the containment and safe disposal of H_2S during tests.

CONCLUSIONS

For eight steels tested at room temperature, rising-load cantilever tests indicated the following:

1. For service in which contact with a corrodent is probable and in which sharp cracks are either present or may develop, steels with yield strengths greater than 140 ksi (965 MN/m^2) are unpredictable in their behaviour and can show a pronounced reduction in properties because of EC.

2. For steels which are cathodically protected, and in which a sharp notch or crack is present or develops, EC is significant even at the 100 ksi (690 MN/m^2) yield strength level. For yield strengths greater than this, there is a pronounced reduction in properties, and a definite hazard of failure by EC, particularly above 140 ksi (965 MN/m^2).

3. A line-pipe steel with a yield strength of 65 ksi (448 MN/m^2) was highly resistant to EC when coupled to zinc, in agreement with service experience in "sweet" oil and gas transmission pipes that cathodic protection does not by itself cause cracking failures in such grades.

ACKNOWLEDGEMENTS

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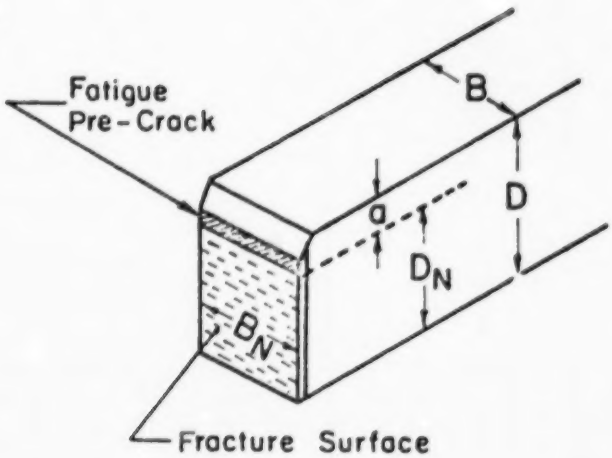
$$K_I = \left(\frac{B}{B_N}\right)^{\frac{1}{2}} \frac{\beta \; L \; w}{B \; D^{3/2}}$$



$$s = \frac{6 \; L \; w}{B_N \; D_N^2}$$

$$\beta = 4.12 \sqrt{\frac{1}{(1 - a/D)^3} - (1 - a/D)^3}$$

K_I	=	Stress Intensity	kpsi $\sqrt{in}$
B	=	Specimen Thickness,	in
B_N	=	Specimen Thickness at Notches,	in
D	=	Specimen Depth,	in
D_N	=	Specimen Depth at Notches,	in
L	=	Total Length of Cantilever Arm,	in
w	=	Total Weight Causing Fracture,	p
s	=	Stress at Notches,	kpsi
a	=	Upper Notch Depth, Including Pre-Crack	in

FIGURE 1. Equations used in this report.

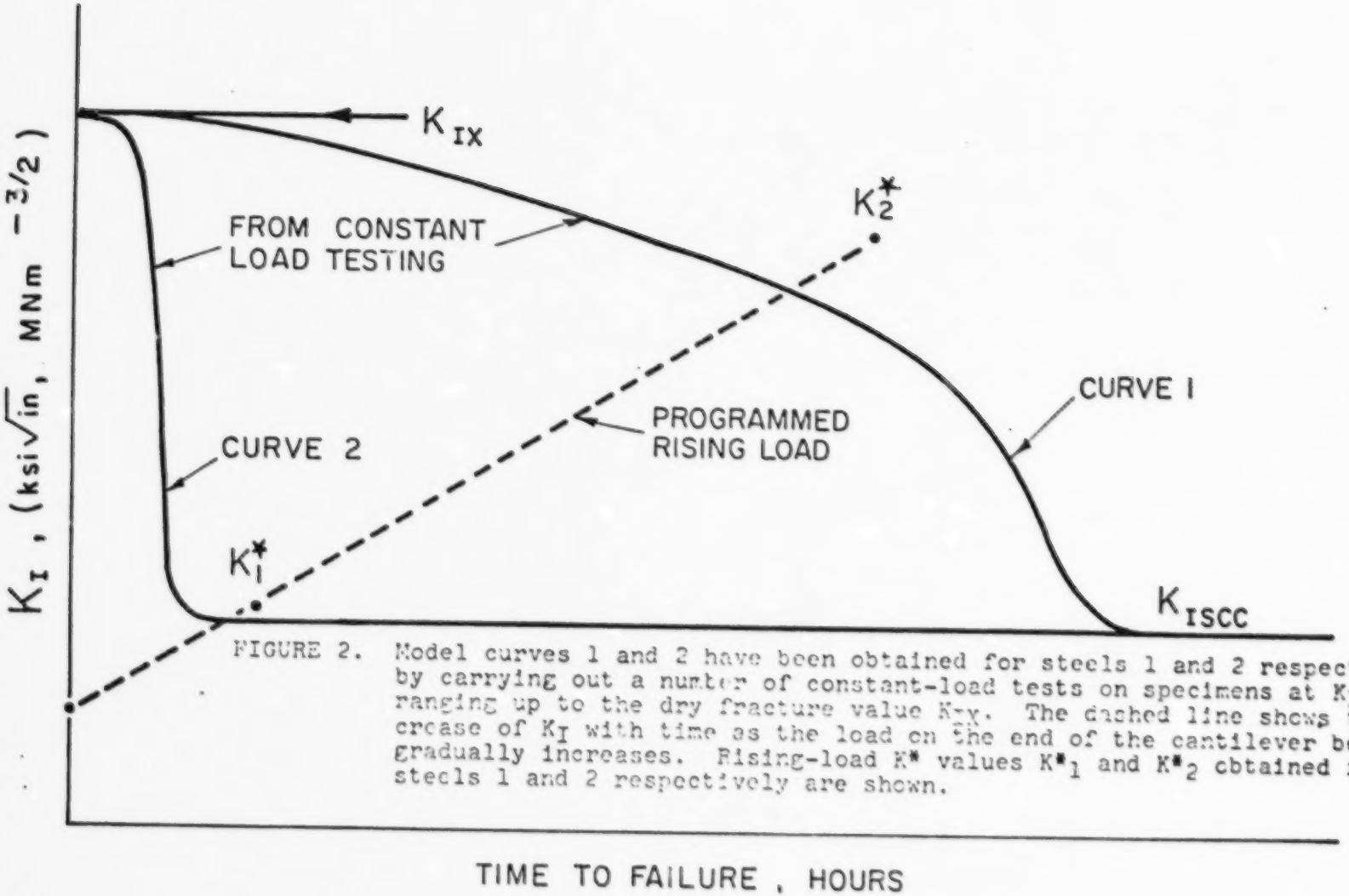
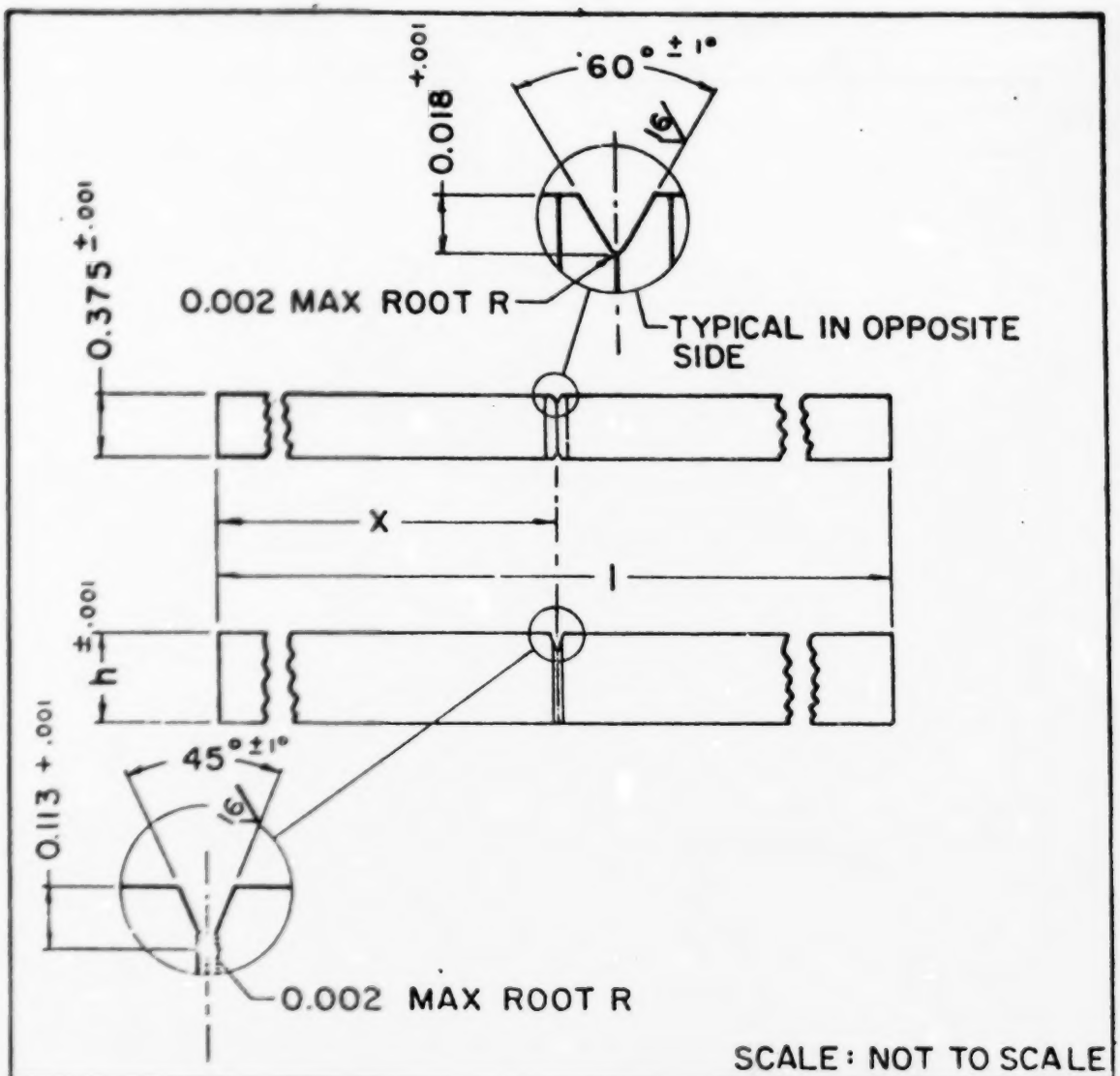


FIGURE 2. Model curves 1 and 2 have been obtained for steels 1 and 2 respectively by carrying out a number of constant-load tests on specimens at K_I values ranging up to the dry fracture value K_{IX}. The dashed line shows the increase of K_I with time as the load on the end of the cantilever beam gradually increases. Rising-load K^* values K^*_1 and K^*_2 obtained for steels 1 and 2 respectively are shown.



US NRL SCC TEST BAR

REMARKS:

DIMENSIONS h, l & X TO BE SPECIFIED.

GENERAL FINISH 125 MICROINCHES MIN. UNLESS SHOWN.

P.M.D. 568 BOOTH ST. OTTAWA

DRAWN BY: H.LETTING

CHECKED BY: H.J.OWEN

MATERIAL:

AS STATED ON WORK ORDER

DWG NO. 119

FIGURE 3. Shop drawing of cantilever test specimen.

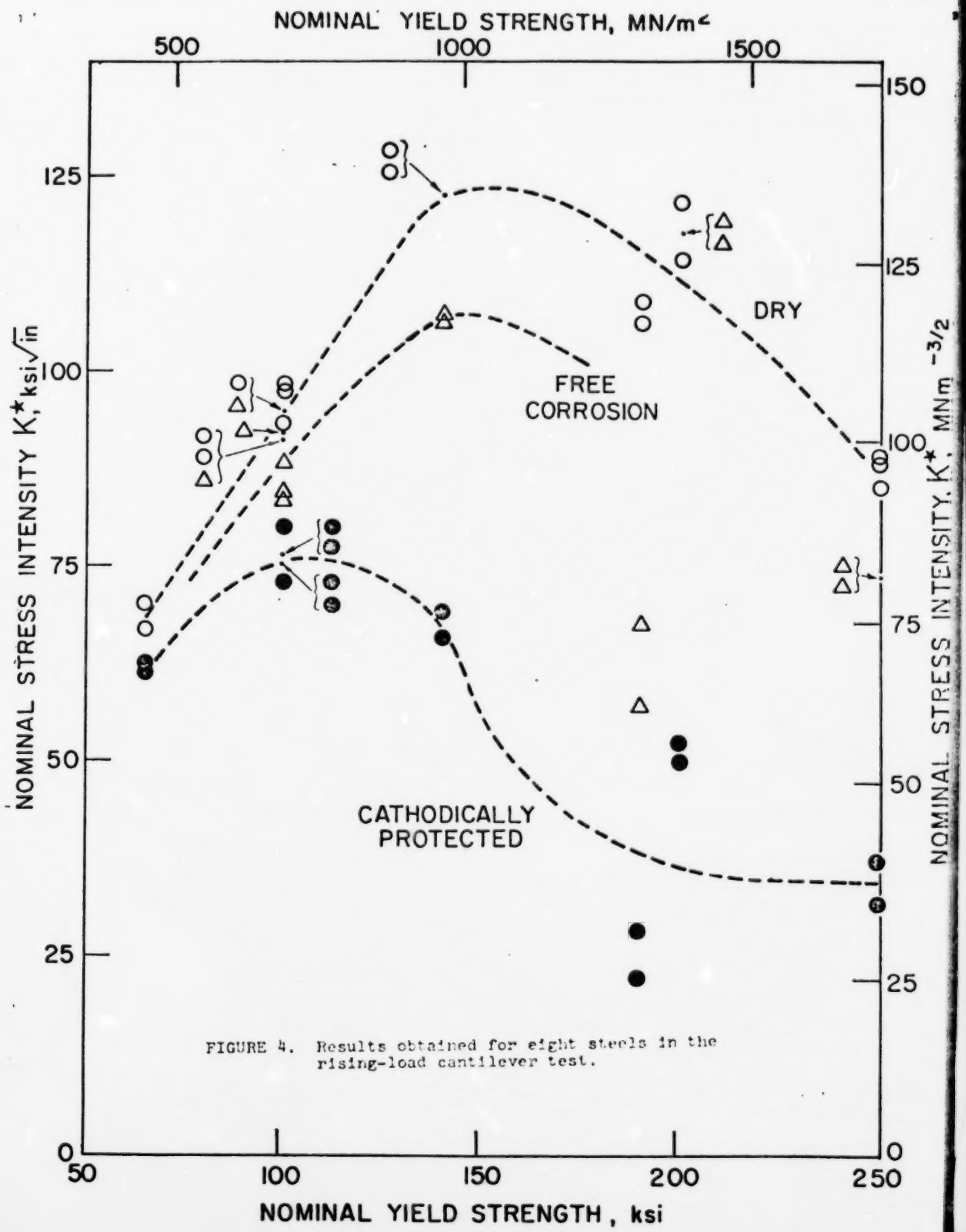


FIGURE 4. Results obtained for eight steels in the rising-load cantilever test.

POOR

QUALITY

ORIGINAL